# COSMOLOGY WITH REDSHIFT SURVEYS OF RADIO SOURCES

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**Abstract.**

We use the $K - z$ relation for radio galaxies to illustrate why it has proved difficult to obtain definitive cosmological results from studies based entirely on catalogues of the brightest radio sources, e.g. 3C. To improve on this situation we have been undertaking redshift surveys of complete samples drawn from the fainter 6C and 7C radio catalogues. We describe these surveys, and illustrate the new studies they are allowing. We also discuss our 'filtered' 6C redshift surveys: these have led to the discovery of a radio galaxy at $z = 4.4$, and are sensitive to similar objects at higher redshift provided the space density of these objects, $\rho$, is not declining too rapidly with $z$. There is currently no direct evidence for a sharp decline in the $\rho$ of radio galaxies for $z > 4$, a result only barely consistent with the observed decline of flat-spectrum radio quasars.

## 1. Introductory remarks

The few column inches devoted to radio galaxies by Peebles (1993) reflects a common view that they are objects of rather peripheral interest to cosmology. Nevertheless, because of the ease with which they can be found at high redshift, they have become popular objects to study. Many ($\sim 100$) are now known at $z > 2$, and the most distant of these (at $z = 4.4$, Rawlings et al. 1996) is not far from the $z = 4.9$ record for quasars. The days when radio galaxies were the only known galaxies at high redshift are, however, now over (Steidel et al. 1996).

Radio galaxies may still allow some special insights into questions of cosmological interest. The most likely low-$z$ counterparts of the $z > 3$ population discovered by Steidel et al. are the spheroids of early-type spirals (Trager et al. 1997). Radio galaxies, on the other hand, at low- and intermediate-$z$ seem to be associated exclusively with giant elliptical galaxies. By studying them at high $z$, one can

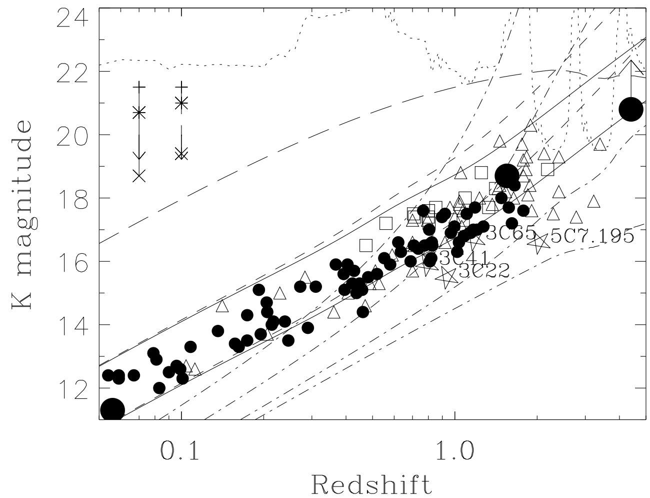


*Figure 1.* The $K-z$ relation for radio galaxies from 3C (filled circles), 6C (triangles), 7C (squares), confirmed 'red quasars' (stars), and as large filled circles: Cyg A, $z=0.056$; 53W091, $z=1.55$; 6C0140+326, $z=4.41$. The solid lines bracket non-evolving ($k$-corrected) ellipticals with luminosities between $M_*$ and $M*-2$ (a typical BCG value) for $\Omega_{\rm M}=1$; the dashed lines are for $\Omega_{\rm M}=0$. The vectors show the expected brightening with look-back time due to passive stellar evolution from $z=0$ ('+') to $z=1$ ('*') to $z=4.4$ ('×'): $\Omega_{\rm M}=1$, left; $\Omega_{\rm M}=0$, right. The dot-dash lines show the loci of 3C quasars reddened by $A_V=0,2,7,15$ (bottom to top). The long-dash line shows the loci of the scattered light from a 3C quasar assuming that the scattering is by optically thick dust with a covering factor $\approx 0.01$, and a $\lambda^{-2}$ dependence for the scattering efficiency (e.g. Ogle et al. 1997). The dotted line shows the expected contamination due to narrow emission lines (for 3C objects), with line ratios taken from composite spectra of high-$z$ radio galaxies and, at low redshift, from an unpublished spectrum of Cyg A.

hope to learn about the formation and evolution of massive ellipticals, and perhaps constrain cosmological parameters (e.g. the study of 53W091 by Dunlop et al. 1996). Although other techniques for finding high-$z$ ellipticals are beginning to show promise (e.g. Graham & Dey 1997), radio galaxies may continue to trace the most massive galaxies and clusters at high redshifts.

## 2. The need for redshift surveys fainter than 3C

The near-IR ($K-z$) Hubble Diagram for radio galaxies *is* discussed by Peebles (1993), and acts as a good focus for an examination of the possible pitfalls of cosmological studies based entirely on surveys of the brightest radio sources. The $K-z$ relation for 3C galaxies is included in Fig. 1.

We consider first the implications of assuming that the $K$ magnitudes of all the 3C objects plotted in Fig. 1 are dominated by starlight (quasars, i.e. objects with broad optical emission lines, have been excluded). As discussed by Lilly & Longair (1984), the highest redshift 3C galaxies are about 1 magnitude more luminous than their low $z$ counterparts. This can be interpreted in one of two ways. Either the 3C galaxies are, at all redshifts, similar mass galaxies which brighten systematically with look-back time because of passive evolution of their stellar populations. Or,

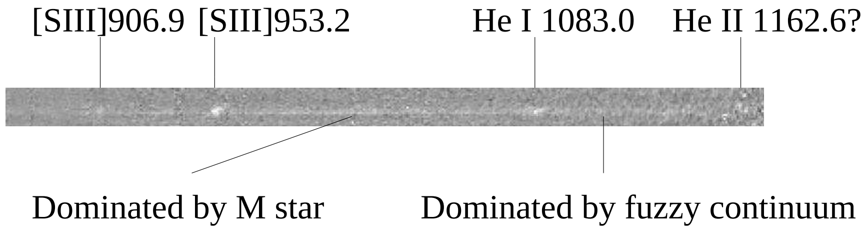


*Figure 2.* A $K-$band spectrum of 3C368 ($z = 1.132$) obtained at the UKIRT; the spatial dimension is 20 pixels ($\approx 24$ arcsec) along PA=8° with North roughly upwards. The [SIII] lines are resolved both spatially (size $\approx 3$ arcsec), and in velocity ($\approx 500$ km s$^{-1}$ shift N-S).

at $z \gtrsim 1$, the 3C galaxies are exclusively ultra-massive brightest cluster galaxies (BCGs) like the host of Cyg A (Fig. 1), whereas at low redshifts they are typically much less massive elliptical galaxies. Some authors argue that both effects are operating (Best, Longair & Röttgering 1997).

But, are the $K$ magnitudes of 3C radio galaxies dominated by old stars? The predicted $K$ values of various non-stellar sources are shown in Fig. 1, these are:

- **Emission lines.** Their huge influence on the $K - z$ relation for $z > 2$ is well documented (Eales & Rawlings 1993,1996), but they also have important effects at lower $z$. In Fig. 2 we present a $K-$band spectrum of the $z = 1.1$ radio galaxy 3C368. Diffuse red continuum is seen in this spectrum (particularly beyond 2.4 $\mu$m where CO absorption dims the foreground M star), but strong [SIII] and Helium lines contribute $\approx 25\%$ of the spatially-extended light, having a strong influence on the appearance of the 'galaxy' (Stockton, Ridgway & Kellogg 1996). Fig. 1 shows that, at $z < 2$, this contaminant can account for at most $\sim 10\%$ of the total $K-$band light of the average 3C galaxy.
- **Buried quasar nuclei.** The broad emission lines discovered in the near-IR spectra of 3C22 (e.g. Rawlings et al. 1995) and 5C7.195 (Willott et al., these proceedings) demonstrate that lightly-reddened ($A_V \sim 1$) quasars can masquerade as narrow-line radio galaxies if classification is based solely on optical spectroscopy. Optical HST images of high-$z$ 3C radio galaxies (Best et al. 1997) probe to $A_V \sim 7$, compared with the $A_V \sim 2$ possible with near-IR spectroscopy, but still reveal a low fraction of lightly reddened quasars (e.g. 3C22). Fig. 1 shows that buried nuclei can still contribute significantly to the $K-$band light provided $A_V \sim 7$. By making the first 3.5-$\mu$m detections of four $z \sim 1$ 3C radio galaxies, Simpson, Rawlings & Lacy (1997) have recently shown that buried nuclei can be an important contributer at $K$, providing $\sim 10\%$ of the light in one case where $A_V > 7$, and $\approx 50 - 100\%$ in the cases of 3C22, 3C41 and 3C65.
- **Scattered quasar light**. Fig. 1 shows that dust scattering of light from a buried quasar, as is now established in Cyg A (Ogle et al. 1997), is also likely to contribute at most only $\sim 10\%$ of the total $K-$band light of $z < 2$ radio galaxies. Such a low level of contamination has been confirmed by the detection of small (at most a few per cent) $K-$band polarizations for $z \sim 1$

3C radio galaxies (Leyshon & Eales 1997).

To this list of non-stellar contaminants one can also add a further, and rather puzzling, source of red radio-aligned light (e.g. Dunlop & Peacock 1993) but again this rarely seems to contribute at more than the $\approx 10\%$ level, and then only in the most extreme (3C) radio sources (Eales et al. 1997).

To conclude, with certain exceptions (e.g. 3C22, 3C41, 3C65), the resolved light profiles of $z \sim 1$ radio galaxies (e.g. Best et al. 1997), and the low ($\lesssim 10\%$) levels of potentially spatially resolved contaminants means that the stellar luminosities of 3C radio galaxies *are* probably higher at high redshifts. However, this may still be a selection effect associated with extreme radio luminosity: the brightest radio sources probably require both the most powerful jets *and* the densest gaseous environments (e.g. Rawlings & Saunders 1991) – environments which are only associated with the most massive brightest cluster galaxies (BCGs).

## 3. The 6C and 7C redshift surveys

We decided several years ago to seek redshifts for low radio-frequency complete samples significantly fainter than 3C. Details of these 6C and 7C samples are given in Table 1, and the improved coverage of the 151-MHz luminosity ($L_{151}$), $z$ plane they provide is discussed by Blundell et al. (these proceedings). The 6C sample has virtually complete redshift information. About 25% of the 7C radio sources are associated with quasars (see Willott et al., these proceedings), and a further 65% have narrow emission lines. These features of the 7C sample again ensure a high redshift completeness ($\approx 90\%$ in the 7C-1 region where spectroscopy has been completed) but are of course a mixed blessing since the emission lines are almost certainly an indication of the AGN activity which, as noted in §2, compromises studies of the 3C sample. In 7C, however, the AGN contamination is at a lower level: the radio/optical correlation for radio quasars (Serjeant et al. 1997), and associated narrow-line/radio correlations for radio sources (e.g. Rawlings & Saunders 1991), suggest that the loci of the three non-stellar contaminants in Fig. 1 should scale as $S_{151}^{p}$ with $p \approx 0.6$, and these should have little influence on the $K - z$ relation, at least for $z < 2$.

About $\approx 10\%$ of the 7C sources will lack secure redshifts even after completion of our spectroscopic campaign. These objects have already been imaged in several near-IR colours, and we find that most have the spectral energy distributions typical of galaxies with $z \sim 1.5$, evolved stellar populations, and weak/absent emission lines. In other words, these galaxies are very similar to 53W091 (Dunlop et al. 1996), and, with large-telescope follow-up, may together provide an even stronger constraint on the age of the high-$z$ Universe.

## 4. Cosmology with the 6C and 7C surveys

Here, we will only discuss some of the implications from the $K - z$ relation from these new redshift surveys (other results are presented by Blundell et al. and Willott et al., these proceedings). $K-$band photometry of the 7C-1 and 7C-2

TABLE 1. Details of the redshift surveys

| Survey | Radio limit | Sky area (sr) | No | Redshifts | Filter |
|---|---|---|---|---|---|
| 3C | $S_{151} > 12$ | 4.2 | 173 | 100% | None |
| 6C | $4 > S_{151} > 2$ | 0.1 | 63 | 97% | None |
| 7C-1 (5C6) | $S_{151} > 0.5$ | 0.0065 | 39 | 90% | None |
| 7C-2 (5C7) | $S_{151} > 0.5$ | 0.0065 | 40 | 65% | ‡None |
| 7C-3 (NEC) | $S_{151} > 0.5$ | 0.0086 | 54 | 70% | ‡None |
| 6C* | $2 > S_{151} > 1$ | 0.133 | 34 | 60% | ‡$\alpha > 1$, $\theta < 15''$ |
| 6C** | $S_{151} > 0.5$ | $\approx 0.2$ | $\approx 100$ | 15% | ‡$\alpha > 1$, $\theta < 10''$ |

‡This means that spectroscopy has yet to be attempted on all members of these samples.

galaxies has only just been completed, so we will focus our discussion on the (mainly 6C) data available at the time of the Tenerife meeting (Fig. 1; see also Eales & Rawlings 1996; Eales et al. 1997). Preliminary analysis of the new 7C data indicates that we will eventually have a much sounder statistical basis for our conclusions.

At $z \sim 1$ the separation of 3C and 6C/7C points in Fig. 1 indicates that 3C radio galaxies *are* brighter by virtue of their extreme radio luminosity. It remains unclear whether this effect is due to contaminant light sources or to the 3C objects being associated with more massive galaxies. However, considering the total spread in stellar luminosities of radio galaxies there now seems little evidence for any evolution between $z \sim 0$ and $z \sim 1$. At either epoch the magnitudes of the radio galaxies are sandwiched between those of an unevolved $M_*$ galaxy and an unevolved BCG. We are therefore led to two possibilities: either (i) $\Omega_{\rm M} = 1$ and the brightening with look-back time due to passive stellar evolution is cancelled by the effects of accretion by mergers; or (ii) $\Omega_{\rm M} < 1$. We plan to use high-resolution near-IR imaging to distinguish between these possibilities.

The curves of Fig. 1 indicate that one has to worry much more about all the contaminant light sources in any interpretation of the $K - z$ diagram for $z > 2$ . It is not yet clear whether the large increase in dispersion is indicative of a wide range of ages in radio galaxies for $z > 2$, and thus whether they are being seen at times when they were young and/or forming (Eales & Rawlings 1996).

## 5. Filtered 6C redshift surveys

Our new 6C and 7C redshift surveys have gone a long way towards breaking the degeneracy between $L_{151}$ and $z$ in the study of radio galaxies, and have extended the redshift coverage by complete samples to encompass the range $2 < z < 3$. They include, however, just 2 objects at $z > 3$. This is largely a consequence of the limited sky area of these surveys. In tandem with our complete sample work we have also been undertaking redshift surveys of larger areas at flux levels comparable to that of the 7C survey. To ensure optical follow-up is confined to

a manageable number of sources requires that we filter out some large fraction ($> 90\%$) of the sources using radio selection criteria. The filtering criteria we have used for our 6C* and 6C** redshift surveys are given in Table 2.

Most $z > 3$ radio galaxies have been found from samples which exclude all the sources with radio spectral indices $\alpha$ flatter than some critical value, and with radio angular sizes $\theta$ greater than some critical value. Choosing these values involves a trade-off between the 'efficiency' (i.e. the fraction of the sample which lies at $z > z_{\rm target}$), and the incompleteness (i.e. the fraction of the $z > z_{\rm target}$ population which has been rejected by the filtering criteria). When $z_{\rm target} = 2$ we can assess these factors by comparing the 6C* sample with a sub-set of the 7C survey which is matched in $S_{151}$: this comparison suggests that about 80% of the $z > 2$ population (meeting the $S_{151}$ criteria) has been missed by 6C*, mostly because of the $\alpha$ criterion, but that 6C* is twice as efficient ($\approx 40\%$ *versus* $\approx 20\%$ for 7C) at finding $z > 2$ radio galaxies.

When $z_{\rm target} \geq 3$ the lack of objects in the complete samples precludes a similarly direct assessment. However, since the $z > 3$ radio sources will all lie at the top of the radio luminosity function (RLF) we can compare their $\alpha$ and $\theta$ properties with those of the most radio-luminous 3C galaxies (Fig. 3). Most objects have concave radio spectra like Cyg A, so the $k$-correction means that an $\alpha > 1$ criterion should exclude only a minority of the $z > 3$ objects. A $\theta < 10$ arcsec criterion requires a strong negative evolution of linear size with $z$ if most $z > 3$ objects are to be retained. Statistically speaking there is good evidence for just such an evolutionary trend (e.g. Neeser et al. 1995; Blundell et al., these proceedings), but an intrinsic spread in $\theta$ means that at least some $\theta > 10$ arcsec sources are already known at $z > 3$ (Fig. 3). We suspect, therefore, that the $\theta$ selection criteria of our 6C* and 6C** surveys are likely to be just as severe causes of incompleteness as those due to the $\alpha$ criteria, especially if $\Omega_{\rm M} = 1$. The influences of filtering criteria need to be considered very carefully, especially if one is to use filtered samples in any analysis of the space density of high-$z$ radio galaxies.

Despite our concerns about incompleteness, the 6C* survey did lead to the discovery of 6C0140+326 at a redshift of 4.41 which is the most distant radio galaxy currently known (Rawlings et al. 1996). Allowing for passive stellar evolution the galaxy seems too faint to be either a well-formed giant elliptical or an unobscured star-forming elliptical in an $\Omega_{\rm M} = 1$ cosmology (it has only a $K$ limit in Fig. 1). Either then we invoke some complicated interplay between the dynamical status of the galaxy, the age of its stellar population and/or the presence of dust, or, as argued in §4, we consider models in which $\Omega_{\rm M} < 1$.

## 6. The space densities of high-redshift radio galaxies

Another cosmological use for radio sources is in the pinpointing of the rapid decline, or 'redshift cut-off', in the co-moving space density $\rho$ of massive (and hence radio-luminous) galaxies expected at $z \sim 5$ (e.g. Efstathiou & Rees 1988). By utilising all the data available at the time (e.g. redshift surveys and source counts), Dunlop & Peacock (1990) found some evidence that steep-spectrum radio galaxies decline in $\rho$ beyond a peak at $z \sim 2.5$. However, given the many difficulties involved with

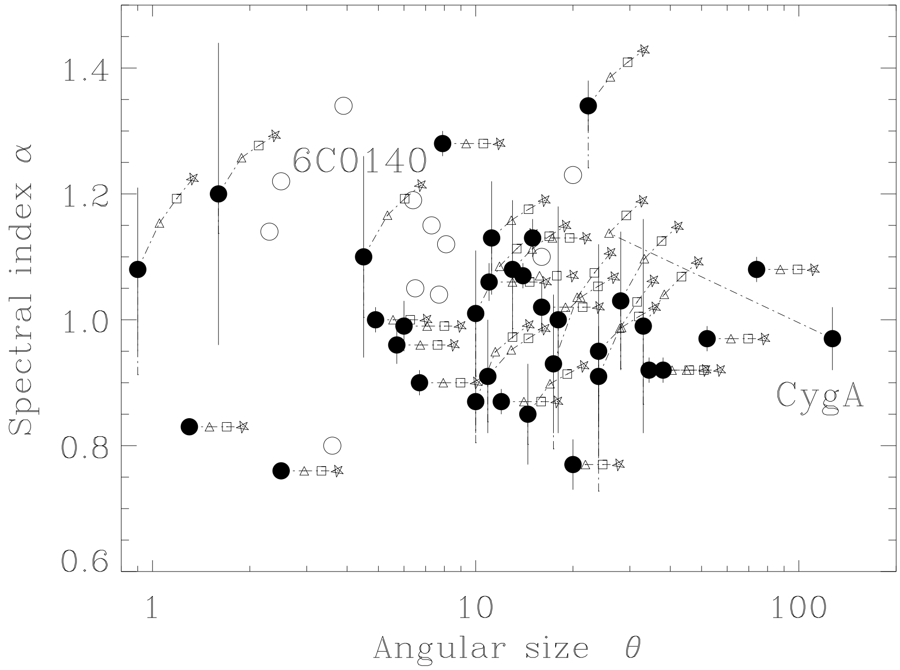


*Figure 3.* The radio spectral index $\alpha$ (evaluated at 1 GHz), angular size $\theta$ (in arcsec) plane for 3C radio galaxies (filled circles, Cyg A marked) and the $z > 3$ radio galaxies known prior to the Tenerife conference (open circles, 6C0140+326 marked). For the 3C sources we have used their integrated radio spectra and observed angular sizes to predict the loci of similar radio sources at $z = 3$ (triangles), $z = 4$ (squares) and $z = 5$ (stars); we assume $\Omega_{\rm M} = 1$.

this work (e.g. radio $k$-corrections, redshift estimates, small number statistics) even the most hardened advocates of a global redshift cutoff might concede that for the most radio-luminous steep-spectrum population at least, the evidence is not yet conclusive. The evidence for a significant decline in $\rho$ for flat-spectrum radio quasars appears to be considerably firmer (Dunlop & Peacock 1990), indeed possibly now incontrovertible (Shaver et al. 1996).

We have begun our analysis by asking a very simple question. If we concentrate on the most radio-luminous galaxies, do we see any direct evidence for a sharp decline in $\rho$? Fig. 4 shows that as yet we do not: our discovery of 6C0140+326 (and the fact that the other known $z > 4$ radio galaxy, Lacy et al. (1994), was found from a 0.2 sr survey), implies that $\rho$ is roughly constant over the redshift range $1.3 \leq z \leq 4.5$. These results are only barely consistent with the rapid decline in $\rho$ for flat-spectrum radio quasars (Fig. 4): a full understanding of the suspected gravitational lensing of both the known $z > 4$ radio galaxies (Lacy et al. 1994, Rawlings et al. 1996) may help bring these results into closer accord. Fig. 4 gives us some hope that the 6C** survey will include at least one radio galaxy at $z > 5$.

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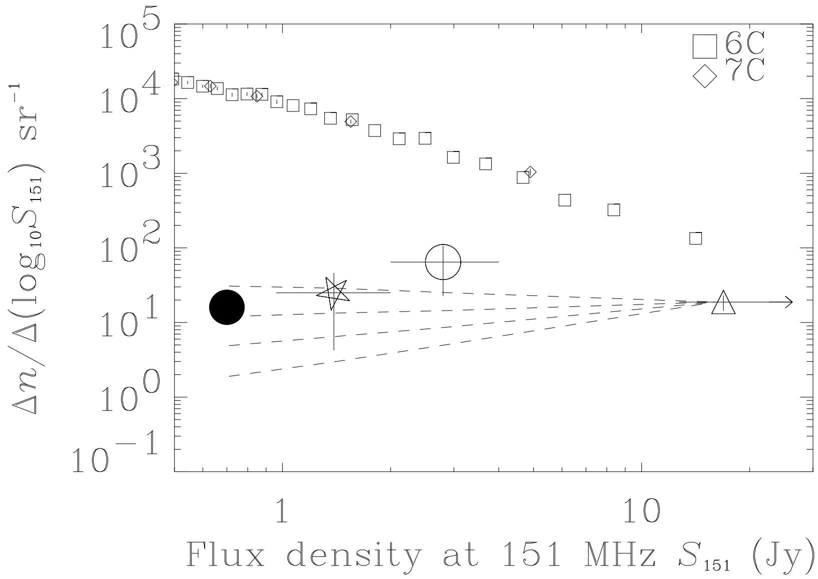


*Figure 4.* Areal density of high-$z$ radio sources (in the top decade of the RLF) as a function of $S_{151}$. The upper data show the total 6C and 7C source counts. The lower points represent: 3C radio sources at $z > 1.3$ (triangle); 6C sources at $z > 3$ (open circle); 6C* sources at $z > 4$ (star); and a point corresponding to 1 radio source at $z > 5$ in 6C** (filled circle). The dashed lines illustrate how this depends on the strength of the redshift cut-off from *(upper)* no cut-off to *(lower)* a cut-off as strong as that seen in the flat-spectrum population (Shaver et al. 1996).


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